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SUMMARY

The thermal stress field of a two piece turbine shroud seal concept was analyzed and compared to two other constrained shroud seal systems by finite element analysis (FEATS). The concept investigated is one in which the two components are fabricated independently and then assembled at ambient conditions. Initial clearance in the attachment region between the ceramic and high temperature metallic alloy substrate is eliminated by expansion mismatch to a desired clamping load. By not constraining the two different materials the thermal stress in the ceramic is minimized. The reduction in stress enhances the reliability for critical turbine components.

The material properties used in the computer code for the ceramic components were those of plasma sprayed yttria-stabilized zirconia (YSZ). The thermal stress analysis was performed for hot side boundary temperatures of 1370 and 1650 °C (2500 and 3000 °F) while the cooled side of the seal was maintained at 700 °C (1285 °F). The seal systems were assumed to be stress free at ambient conditions and the model was not rigidly fixed to other structural members.

The two constrained seal concepts (top layer of ceramic applied by plasma spraying) that were used for comparison were the graded layer and the strain isolation layer concepts. At the steady state conditions imposed, the thermal stress results indicated that the stress in the ceramic layers of the two rigidly constrained seal systems was a large percentage of the strength of the material.

The two piece shroud seal concept was analyzed for the same conditions imposed on the other two seal systems. The results of the thermal stress analysis indicated that the maximum stress level in the two piece concept was much less than what was found in either of the constrained seal systems analyzed.

INTRODUCTION

The purpose of the turbine shroud seal, as used in jet engines, is to provide an annular seal around the rotating turbine blades (fig. 1). An increase in insulating and sealing qualities provides more engine thrust while increasing engine efficiency. Both gains can be realized in lowering the operational costs of a typical gas turbine engine (ref. 1). The turbine shroud seal has evolved from an all metallic high temperature alloy structure to a combination of the metallic alloy with ceramic materials.

The most recent advance in this type of seal has been to use ceramics and high temperature alloys together. Currently these materials are being used by

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plasma spraying the ceramic material onto the high temperature alloy base (substrate). This arrangement allows combustion gas temperatures to be increased and at the same time decreases the amount of cooling flow needed from the compressor.

The disadvantage of plasma spraying ceramics on metallic alloy substrates is the differences in the thermal expansion rates of the different materials used. These differences can cause large thermally induced stresses to exist in the plasma sprayed layer (ref. 2). The thermal loading can cause the coating to spall or separate from the metallic alloy. Many attempts have been made to reduce the chance of spalling of the ceramic layer. Two of the possible methods of relieving thermal stresses are: (1) the graded layer seal design (ref. 3) in which the metallic and ceramic are graded by the percentage of metallic added to the ceramic, and (2) the strain isolation layer seal design which employs an isolation pad (ref. 4) between the plasma sprayed ceramic and the metallic alloy base (fig. 2).

A two piece shroud seal concept (ref. 5) was examined and is compared to the two other seal systems already discussed (fig. 3(a)). This concept does not have the constraint conditions that are imposed by rigidly fixing coatings on high temperature metallic substrates. The ceramic component would be processed independently and then slid onto the high temperature alloy substrate at room temperature (fig. 3(b)). The clearance between the two components that exists at ambient conditions decreases to impose a clamping load at operating temperatures due to different thermal expansion coefficients of the two components. The amount of ambient temperature clearance is dependent on the expected loading that the two-piece interface will have to resist and would be a critical design variable.

The stress field present in the two piece seal design is due to the thermal gradient that is applied across the seal and the effect of the substrate is considered as a clamping load. The clamping load was simulated as a pressure load on the formed ceramic-substrate interface.

The reduction of stress in ceramic components due to thermal loads will enhance the reliability necessary for turbine engine applications. The use of ceramics in critical components is essential if turbine temperature (performance) is to be increased.

The objective of this work was to evaluate the thermal stress field differences between the strain isolation, metallic graded, and two piece seal systems using a steady state, two-dimensional finite element computer program. Analysis is described and results presented in isostress contours for each configuration.

ANALYSIS

The thermal stress fields present in the various seal systems simulated were calculated by a finite element code. The FEATS code (ref. 6) is a two-dimensional steady state analysis. The stress field that was solved for in the analysis was due to a constant gas side temperature and cooler backside temperature at the two boundaries. The temperature conditions imposed on these boundaries are based on current and expected operating conditions of the turbine shroud seal. Other surfaces without their boundary temperatures specified were assumed to be perfectly insulated. The seal systems were assumed to be stress free at ambient temperature. The residual stress from the plasma spraying operation was assumed to be either annealed out of the plasma sprayed or not present in the formed layers. The specified boundary temperatures along with the material properties, that are a function of temperature, were used by the computer program to solve for the temperature field. Material properties that are not given at a specific temperature are linearly interpolated, or extrapolated, as found in table I. This provided the necessary input for the calculation of the stress field. The anisotropic behavior of the strain isolation layer (ref. 4) was modeled. This behavior had little effect on the magnitude of the stress field of the ceramic layer, and therefore is not reported herein.

The effect of processing techniques on material properties of the two piece concept was assumed to be insignificant. The author considered that the processing technique employed for the two piece seal would yield the same properties as those of the plasma sprayed ceramics.

To minimize the model size, curvature effects were neglected. By considering a unit depth, the model is reduced to two dimensions. By exploiting a line of symmetry, the model size was further reduced. The model was constrained from motion across the line of symmetry. One node at the line of symmetry was constrained from motion in either coordinate direction. Other nodes along the line of symmetry were only constrained not to move across but were permitted to move parallel to this line. Reference 11 has shown that the simpler two-dimensional analysis such as was used in this work produces the same trends as will a much more complicated three-dimensional analysis. The elemental sizes of the models used in the analysis are shown in table II.

Test results are presented using the contour plots of isostress from the finite element analysis. Each plot indicates the maximum and minimum elemental stress value. The elemental stress field values found by the FEATS computer code is then linearly interpolated to the nodes. By interpolation of the elemental (centroidal) stress to the nodes, smoothing of a rapidly changing stress field occurs.

RESULTS AND DISCUSSION

Graded Layer and Strain Isolation Seal Concepts

The graded ceramic-metallic layer concept is one method of reducing the thermal expansion discontinuities present in plasma sprayed ceramic layers (ref. 3). By introducing metallic material (i.e., CoCrAlY) into the ceramic layer (in varying percentages during the plasma spraying operation) the large difference between expansion characteristics is reduced while the insulating effect of the ceramic is maintained.

The strain isolation concept is another possible method of attaching a plasma sprayed ceramic insulating surface to a metallic structural member (ref. 4). The strain isolation material is made of a high temperature alloy material (i.e., Hastelloy X, Hoskins 875) that has a high amount of porosity (typically 65 to 75 percent). The porous layer provides the low modulus mechanical connection between the ceramic top layer and the metallic alloy structure. The low modulus material allows relative movements of the two thermal expansion mismatched materials allowing stress levels to be minimized.

The two systems discussed both have drawbacks associated with their implementation. First, the graded metallic-ceramic plasma sprayed layers have relatively large stresses associated with the plasma sprayed layer changes. These levels reach a substantial portion of the material strength at operating temperature. Secondly, the strain isolation layer is a metallic alloy with a large amount of internal surface area that is available for strength degradation due to oxidation at high temperatures.

The results of the finite element analysis are shown for these two systems on figure 4. Axial stress dominates over the radial stress on both the graded and strain isolation layer seals. The stress field shown here for either system would not cause the seals to fail, however the steady state boundary temperature conditions that are used for comparison in the this study are not the most severe that the seal encounters. The most severe conditions have been shown to occur in the deceleration transient from maximum power to idle (ref. 11), but this case is beyond the scope of this work.

Two Piece Seal Concept

The two piece seal design is one in which the two main components are not rigidly connected during the fabrication process. The ceramic shroud segment of this seal system would not be plasma sprayed but would be manufactured by an alternative ceramic forming operation. The segment could be made in a near net shape that would minimize the amount of post curing machining. Two of the possible methods that could be implemented include injection molding and hot isostatic pressing. These forming techniques and the proper control over ceramic composition would enable the production of reliable components produced with the desired material properties (ref. 12).

The structural component of this seal concept could be made from Hastelloy-X or some other high temperature alloy material. At room temperature there would be clearance to allow assembly of the seal (fig. 3). The clearance between the ceramic and high temperature alloy would depend on the of clamping load needed as well as the stress that could be tolerated. Until steady state conditions are reached the ceramic component could be held by a radial pin that would prevent circumferential motion of the ceramic. The arrangement for the two piece seal design could be further simplified by having only one slot instead of two as was used in this analysis.

Two Piece Stress Results

To enable a realistic comparison between the finite element results of the previous seal systems discussed, the two component seal was subjected to similar conditions. The same overall dimensions and line of symmetry were used. An important difference between the models discussed here is that the two piece seal has a rail that connects the metallic alloy structure together across the line of symmetry. This allows the ceramic to be minimally affected by loading between the seal and the rest of the engine structure.

To investigate the thermally induced stresses found in the solid ceramic seal component the temperature distribution for the ceramic was first found by analyzing the slotted ceramic and substrate as though they were rigidly attached. This provided the nodal temperature field necessary to allow the finite element analysis of the solid ceramic to be evaluated without the metallic alloy substrate present. One difficulty encountered in this procedure was where the cooling side boundary condition was imposed for the temperature field analysis. The same cooled side temperature was imposed on the backside of the metallic alloy and on the backside of the solid ceramic and the thermal stress compared (fig. 5). The stress distribution shown in figure 5 indicates that differences between the two boundary conditions are minimal. In figure 6 the effect of hot gas boundary condition change is shown. The change in this boundary condition to the high temperature gas side surface temperature causes the magnitudes of stress components to increase. The results from figure 6(a) can be used as a comparison of stress field to the results of the other two seal concepts shown in figure 4. The difference in magnitudes between the two figures is apparent, with stresses in the two piece seal being substantially lower than in the other two designs.

The effect of pressure loading between the substrate and ceramic element has been omitted up to now. This was done to investigate the thermal loading effects separately and then add the substrate's effect to the analysis. To simulate the loading effect on the slot region, pressure was applied to surfaces in this region of the finite element model. Figure 7 presents this effect in the ceramic with and without pressure loading. The pressure loads were applied such that the sum of the pressure loads would not violate static equilibrium. The magnitude of the pressure load was chosen only as an example and was not representative of a particular application. The analysis shows that the slot pressure increases the magnitude of stress in the ceramic. The magnitude of the stresses present due to the slot and the pressurized slot are still much lower than that from the other two seal concepts in the top ceramic surface near the high temperature side of the seal.

From this analysis it is concluded that the two piece seal concept has lower total stress due to thermal loading than the other two concepts. This is due to the absence of rigid constraint put on the ceramic layer.

Design Implications

Through the use of more advanced and complex finite element modeling for a particular seal environment it would be possible to determine the assembly clearance needed. The clearance between the two components is dictated by the amount of clamping required for the environmental conditions present. The size and shape of the slot which was not changed for the results presented could be optimized to allow further reduction in the stress field present. The two component seal concept is just one application of possible high temperature environment uses that uniform property produced ceramics could be used for in a two piece form.

SUMMARY OF RESULTS

Three different seal system concepts were analyzed using a two-dimensional steady state finite element computer code (FEATS). The seal concepts included two constrained layer concepts as well as a new concept with an unconstrained layer. The two constrained layer seals analyzed were the graded layer and strain isolation layer designs both having a high temperature alloy substrate. The new concept seal consisted of a formed ceramic seal attached by a retainer system, having clearance for assembly at room temperature, and prevented from rotating by an antirotation pin.

For all three designs, a thermal stress analysis was performed. The boundary conditions included a maximum temperature at the hot side of 1650 °C (3000 °F) while the cool side was at 700 °C (1285 °F). Other surfaces were perfectly insulated and no external loads or structural connections were assumed.

The following results were obtained

1. The thermal stress field of the seal could be reduced by not constraining the ceramic material to the substrate as is done by current techniques employing plasma sprayed ceramics.

2. The effect of a clamping load in the slot region of the ceramic seal was included as part of the finite element boundary conditions and indicated that the stress present in the ceramic would increase. However, the magnitude of stresses present even with pressure loading in the retainer slot were much lower than that found from the thermal loads on either the graded layer or the strain isolation layer designs in the region of all ceramic material.

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TABLE I - VARIATIONS IN MATERIAL PROPERTIES USED IN FINITE ELEMENT CODE

Temperature		Modulus of elasticity		Poisson's ratio	Coefficient of thermal expansion		Modulus of rupture[a]		Thermal conductivity	
°C	F	N/mm^2	psi		m/m °C	in/in °F	N/mm^2	psi	W/m C	Btu/ft hr °F
Yttria stabilized zirconia (ref 7)										
20	70	28 300	4 1x10^{6}	0 25	9 27x10^{-6}	5 15x10^{-6}	30 6	4 430	-----	-----
93	200	-------	--------	----	----------	---------	-----	------	0 47	0 27
260	500	-------	--------	----	----------	---------	-----	------	45	26
540	1000	-------	--------	----	----------	---------	-----	------	45	26
820	1500	-------	--------	----	----------	---------	-----	------	45	26
1090	2000	-------	--------	----	----------	---------	-----	------	49	28
1370	2500	13 300	1 93	25	10 71	5 95	11 1	1 610	54	31
85 percent yttria stabilized zirconia/15 percent CoCrAly (ref 7)										
20	70	23 100	3 35x10^{6}	0 26	13 23x10^{-6}	7 35x10^{-6}	37 9	5 490	-----	-----
260	500	-------	--------	----	----------	---------	-----	------	0 54	0 31
540	1000	-------	--------	----	----------	---------	-----	------	54	31
820	1500	-------	--------	----	----------	---------	-----	------	55	32
930	1700	21 030	3 05	26	13 23	7 35	34 9	5 070	-----	-----
980	1800	-------	--------	----	----------	---------	-----	------	57	33
40 percent yttria stabilized zirconia/60 percent CoCrAlY (ref 7)										
20	70	68 950	10x10^{6}	0 28	13 5x10^{-6}	7 5x10^{-6}	153 8	22 300	-----	-----
93	200	-------	--------	----	----------	---------	-----	------	1 11	0 64
260	500	-------	--------	----	----------	---------	-----	------	1 26	73
540	1000	-------	--------	----	----------	---------	-----	------	1 51	87
760	1400	30 300	4 4	28	13 5	7 5	161 8	23 500	-----	-----
820	1500	-------	--------	----	----------	---------	-----	------	1 78	1 03
Strain isolation layer (ref 8 except thermal expansion from ref 10)										
20	70	-------	--------	----	13 9x10^{-6}	7 7x10^{-6}	-----	------	-----	-----
93	200	-------	--------	----	----------	---------	-----	------	0 73	0 42
205	400	550	8x10^{4}	0 3	----------	---------	-----	------	-----	-----
425	800	550	8	3	----------	---------	-----	------	92	53
650	1200	550	8	3	----------	---------	-----	------	1 04	60
820	1500	-------	--------	----	14 1	7 8	-----	------	-----	-----
870	1600	550	8	3	----------	---------	-----	------	1 18	68
Hastelloy-X (ref 9)										
205	400	2 14x10^{5}	31 0x10^{6}	0 3	13 0x10^{-6}	7 2x10^{-6}	-----	------	12 7	7 33
425	800	1 97	28 5	3	13 7	7 6	-----	------	17 2	9 92
650	1200	1 79	26 0	3	14 6	8 1	-----	------	21 8	12 6
870	1600	1 55	22 5	3	16 0	8 9	-----	------	26 0	15 0
1090	2000	--------	--------	----	----------	---------	-----	------	28 2	16 3

[a]Experimentally determined in reference 7 by four-point bend test that is used for determining tensile strength of brittle materials

TABLE II. - NUMBER OF ELEMENTS USED FOR FINITE ELEMENT MODELS

Model	Number of elements used
Graded metallic layer	92
Strain isolation layer	92
Ceramic seal insert	70
Two piece seal metal	38

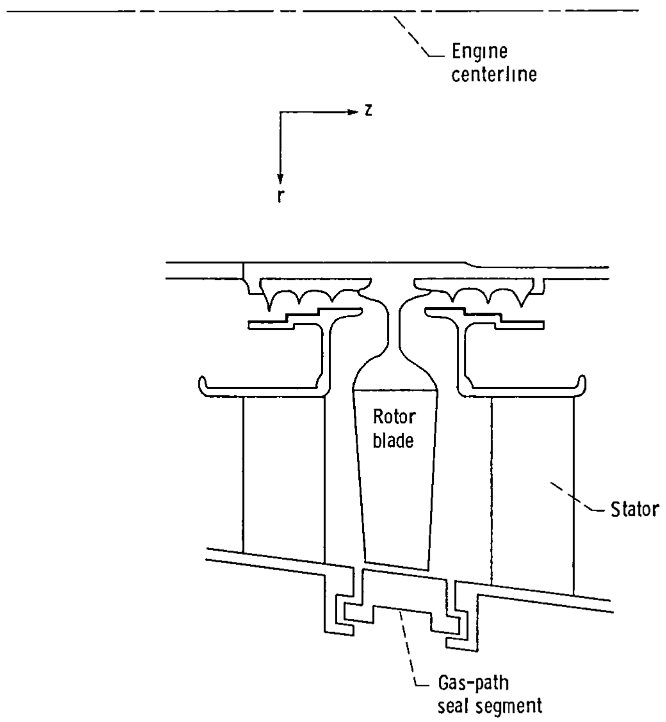
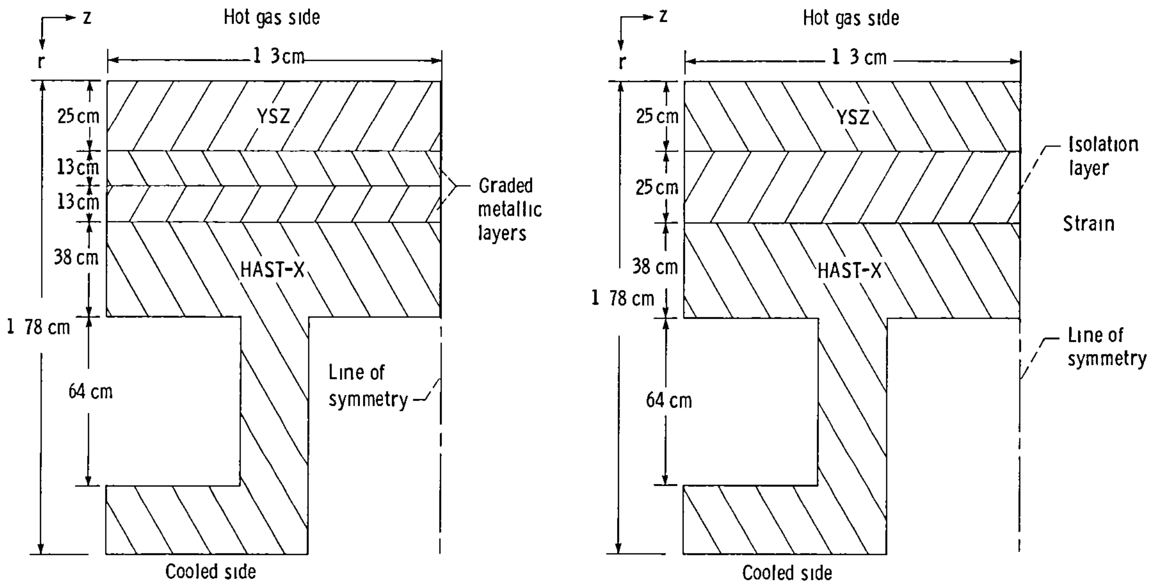


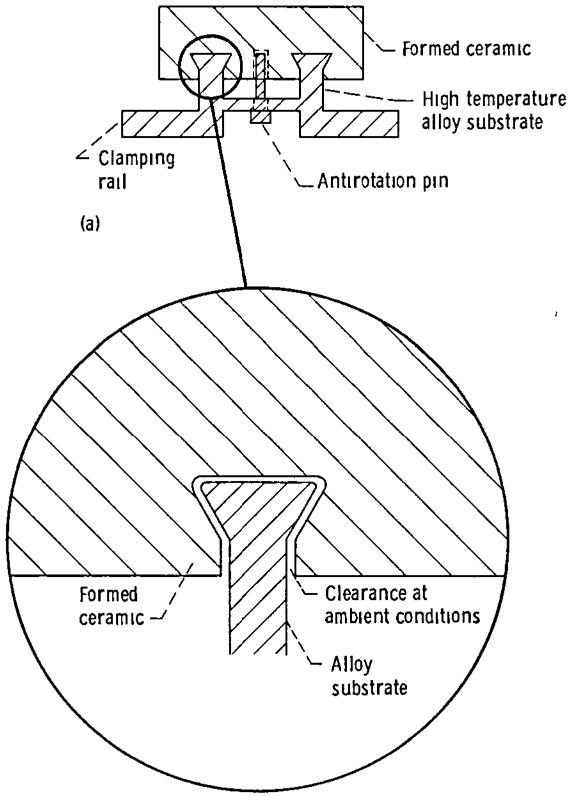
Figure 1 - High-pressure turbine gas-path seal



(a) Graded metallic layer seal

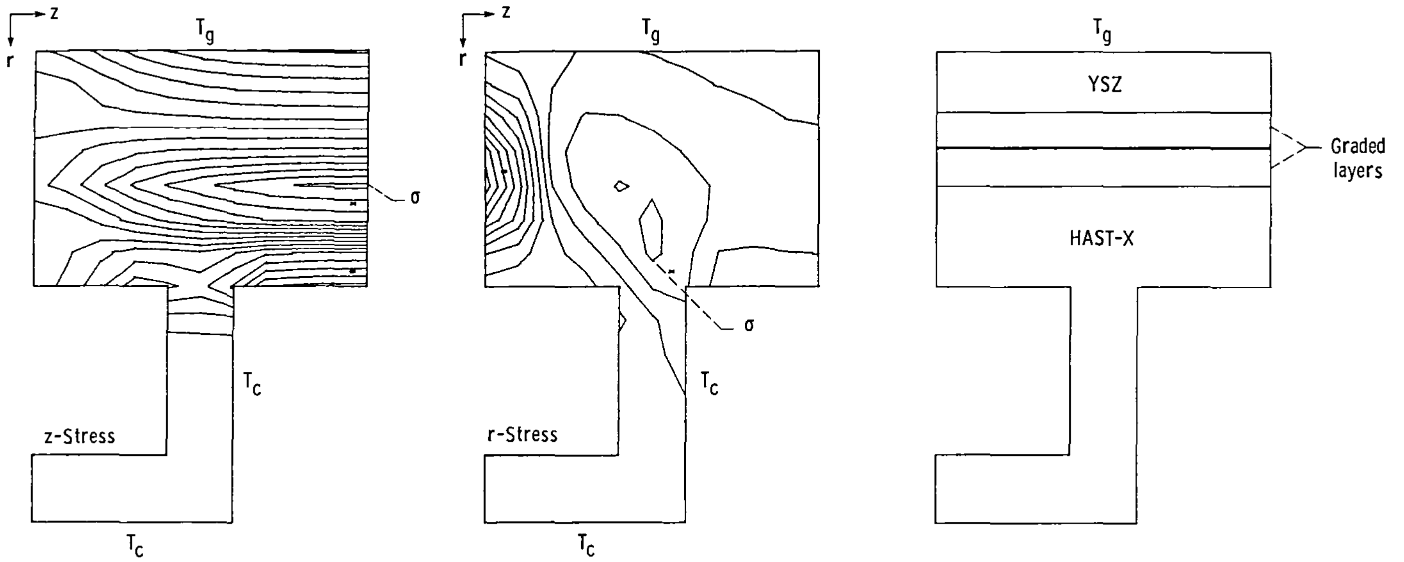
(b) Strain isolation layer seal

Figure 2 - Shroud seal models of current state of the art seals used in high temperature turbine (Axial cross section shown) (z = engine axial direction, r = engine radial direction, YSZ = Yttria Stabilized Zirconia)

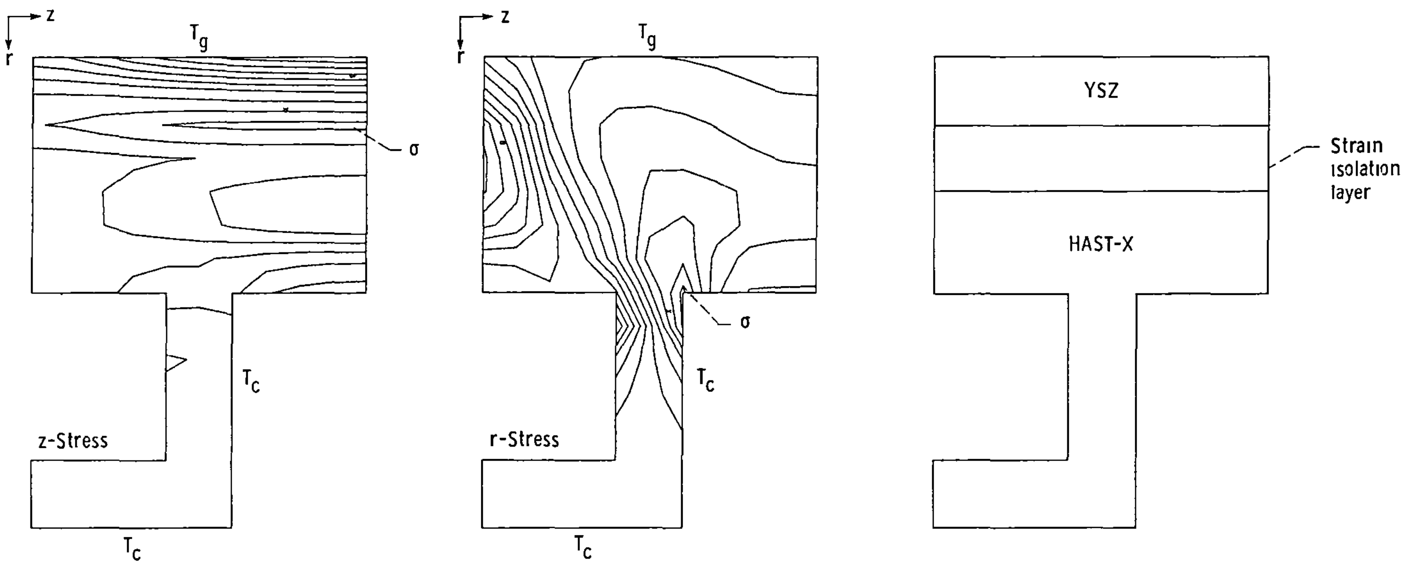


(b) Close-up diagram of substrate-ceramic connection location

Figure 3 - Two piece seal design



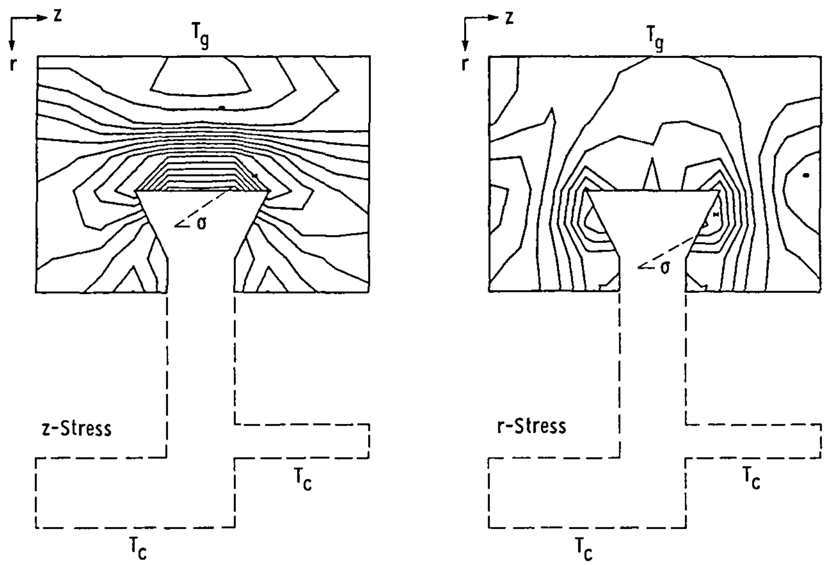
(a) Graded layer seal axial(z) and radial(r) thermal stress



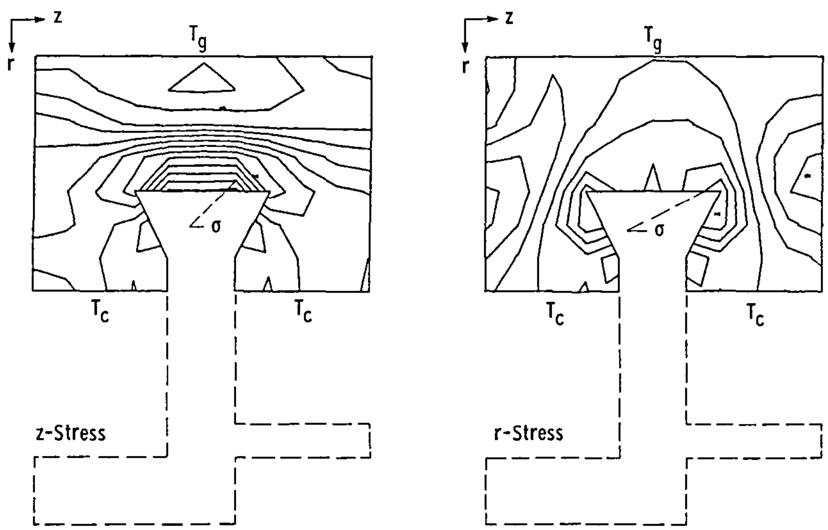
(b) Strain isolation seal axial(z) and radial(r) thermal stress

Seal	Direction	Element stress values		Contour values using nodal stress	
		"x" Maximum MPa (psi)	"o" Minimum MPa (psi)	Increment between contours MPa (psi)	Maximum tension contour "σ" MPa (psi)
Graded layer seal	z r	64 4 (9340) 8 07 (1170)	-57 6 (-8360) -27 7 (-4020)	7.2 (1040) 2 8 (405)	52 7 (7640) 6 1 (880)
Strain isolation	z r	27 7 (4010) 5 7 (825)	-37 2 (-5400) - 6 5 (-940)	5 7 (825) 0 7 (105)	12 8 (1860) 3 9 (560)

Figure 4 - Thermal stress contours for graded layer and strain isolation seals Boundary conditions used were T_g = 1650 °C (3000 °F) and T_c = 700 °C (1290 °F)



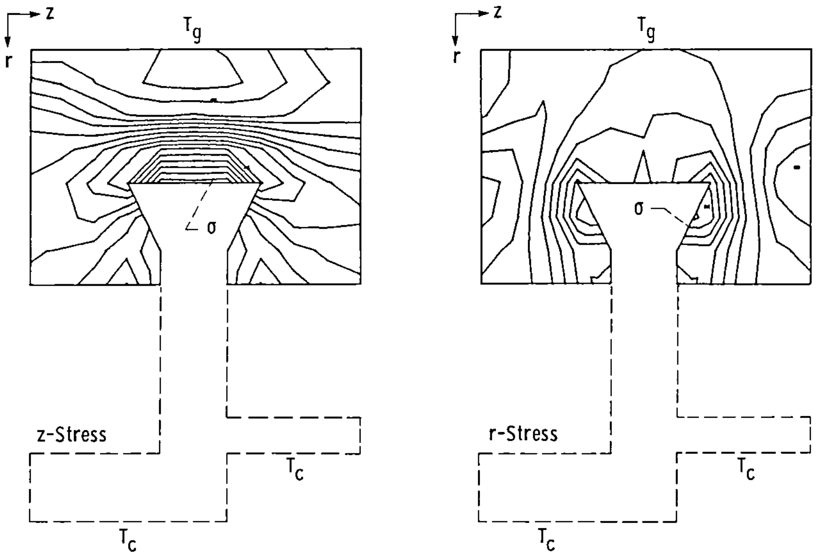
(a) Cooled side temperature on substrate surface



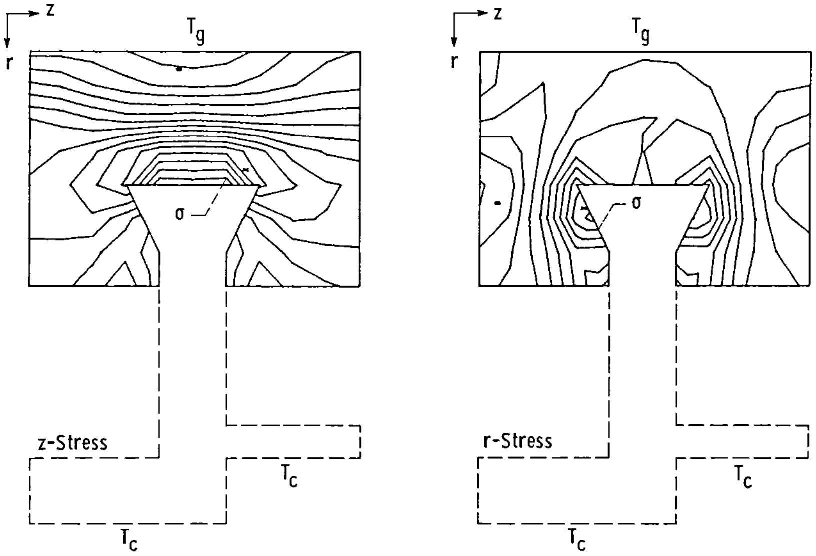
(b) Cooled side temperature boundary condition on the backside of ceramic.

Condition	Direction	Element stress valves		Contour valves using nodal stress	
		"x"-Maximum MPa (psi)	"o"-Minimum MPa (psi)	Increment between contours MPa (psi)	Maximum tension contour "σ" MPa (psi)
Cooled surface on substrate backside (a)	z	7 86 (1140)	-3 96 (-575)	0 7 (102)	7 1 (1030)
	r	6 2 (895)	-2 1 (-300)	0 57 (82)	2 9 (420)
Cooled surface on ceramic backside (b)	z	8 96 (1300)	-4 5 (-645)	1 0 (150)	8 3 (1200)
	r	4 65 (675)	-1 9 (-280)	0 6 (83)	1 9 (270)

Figure 5 - Two piece seal, thermal axial and radial stress contours from boundary condition change where cooled surface was positioned (T_g = 1650 °C (3000 °F), T_c = 700 °C (1290 °F))



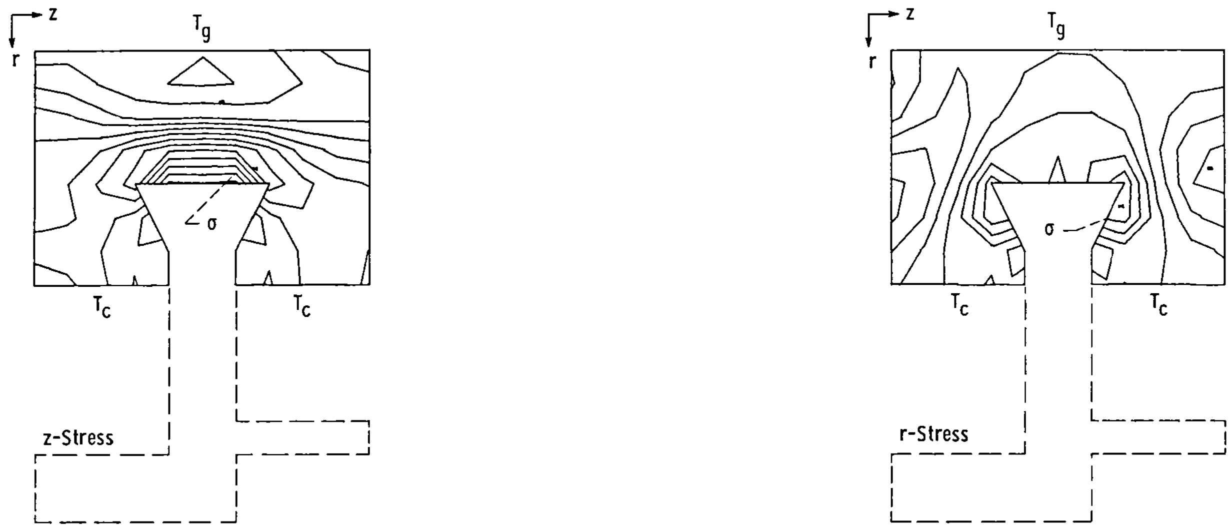
(a) T_g = 1650 °C (3000 °F) surface temperature



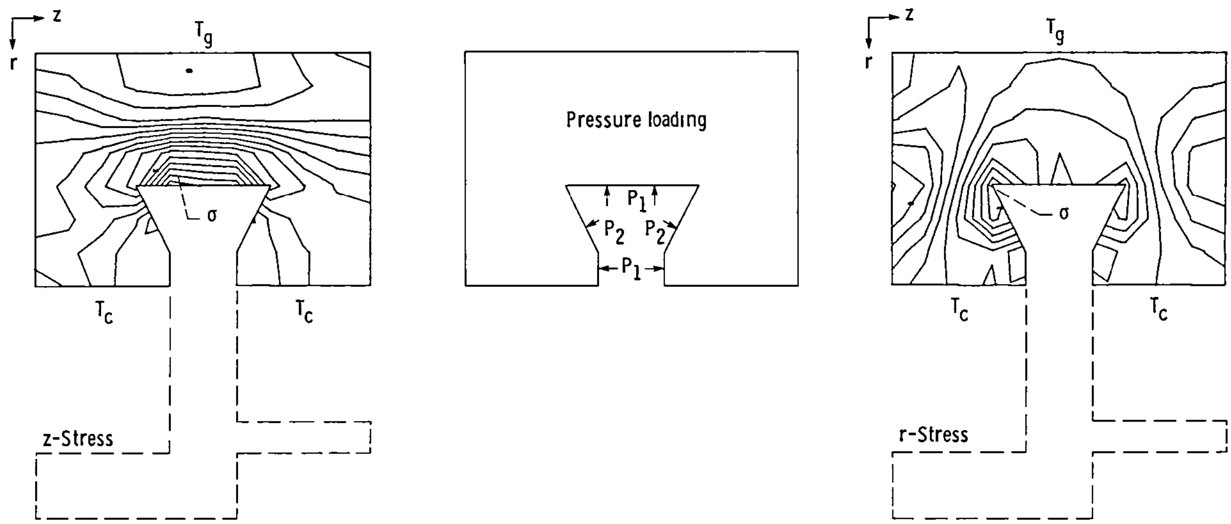
(b) T_g = 1370 °C (2500 °F) surface temperature

Condition	Direction	Element stress values		Contour values using nodal stress	
2-Piece seal		"x"-Maximum MPa (psi)	"o"-Minimum MPa (psi)	Increment between contours, MPa (psi)	Maximum tension contour "σ" MPa (psi)
T_g = 1650 °C (3000 °F) T_c = 700 °C (1290 °F) (a)	z	7 9 (1140)	-3 96 (-575)	0 7 (102)	7 1 (1030)
	r	6 2 (895)	-2 1 (-300)	0 57 (83)	2 9 (420)
T_g = 1370 °C (2500 °F) T_c = 700 °C (1290 °F) (b)	z	5 3 (765)	-3 7 (-535)	0 7 (82)	4 6 (670)
	r	3 9 (570)	-1 5 (-215)	0 36 (52)	2 3 (330)

Figure 6 - Two-piece seal, thermal stress distribution due to gas boundary temperature difference. (T_c = 700 °C (1290 °F))



(a) No pressure in the slot.



(b) Pressure loading in slot. P_1 = 0.69 MPa (100 psi), P_2 = 0.31 MPa (45 psi).

Condition	Direction	Element stress values		Contour values using nodal stress	
		"x"-Maximum, MPa (psi)	"o"-Minimum, MPa (psi	Increment between contours, MPa (psi)	Maximum tension contour "σ", MPa (psi)
No pressure in slot (a)	z	9 0 (1305)	-4 5 (-645)	1 0 (150)	8 3 (1200)
	r	4 7 (675)	-1 9 (-280)	0 58 (84)	1 9 (270)
Pressure in slot (b)	z	11 8 (1715)	-5 1 (-740)	1 05 (152)	9 5 (1380)
	r	6 4 (930)	-2 9 (-420)	0 58 (84)	3 1 (950)

Figure 7 - Two piece seal effect of pressure loading in slot region for T_g = 1650 °C (3000 °F) and T_c = 700 °C (1290 °F)

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15 Supplementary Notes

16 Abstract

The thermal stress field of a two piece turbine shroud seal concept was analyzed and results compared to one piece designs by finite element analysis. The two piece seal has independently formed structure (substrate) and ceramic components that are assembled at ambient conditions. The boundary conditions used for analysis were hot gas surface temperatures of 1370 and 1650 °C (2500 and 3000 °F) and cooled surface temperatures of 700 °C (1285 °F). The resulting thermal stress field, of the two piece seal when compared to the one piece seals in the region of all ceramic material, was reduced substantially.

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